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TECHNICAL NOTE

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LIMITED INVESTIGATION OF CRUSHABLE STRUCTURES FOR ACCELERATION PROTECTION OF OCCUPANTS OF VEHICLES AT LOW IMPACT SPEEDS

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SUMMARY

A limited investigation has been made to determine the characteristics of three materials to see how they can be applied for human protection against accelerations encountered at low impact speeds. As a result, if given man's physiological tolerance to abrupt acceleration, which has not yet been well defined, an alleviation system can be designed.

Foamed plastics require considerable depth to provide a given stopping distance for impact alleviation and their use would require some control of rebound. They can be made soft enough to obtain the low onset of acceleration that may be necessary for man where depth is not limited.

Aluminum honeycomb is an efficient material for impact load alleviation from the standpoint of usable material depth and it exhibits very little rebound. The stiffness of the material results in a very high initial onset rate of acceleration. For many installations this may be controlled by reducing the initial loading area of contact to get the material to start failing.

INTRODUCTION

This report examines the characteristics of three materials to see how they can be applied for human protection against accelerations encountered at reasonably low impact speeds.

The study of impact load alleviation for parachute delivery of supplies and equipment has been in progress since World War II. The alleviation has been in the form of a crushable structure located between the object to be protected and the impact surface. This material is used as an energy absorber and allows the impact load on the object to be felt over a longer distance and time. The use of such materials or structures allows the acceleration at impact to be controlled.

The difference in packaging men and materials lies in the manner in which the energy is absorbed. Protection of supplies and equipment usually requires limiting only the load to some fixed acceleration level. A rectangular time history of acceleration is usually specified as a goal, since this results in minimum peak acceleration for a fixed stopping distance. A typical example of this type of load alleviation is discussed in reference 1. Since man is a series of spring-mass systems, the rate at which acceleration is applied as well as the maximum acceleration are both of importance. The spring-mass concept implies that there might be rates of onset of acceleration (g units) that would result in amplification of the imposed acceleration on certain parts of the body (ref. 2). A reasonable acceleration tolerance suggested for man and indicated from the data collected in reference 3 is an onset rate of 1,500 g/sec to a level of 40 g with a duration of 0.10 second. This time history is for acceleration applied in the direction of spineward to sternumward.

Tests were made with two foamed plastics and an aluminum-honeycomb structure to study their behavior under abrupt deceleration. These materials were dropped from a height of approximately 14 feet (to give an impact velocity of 30 ft/sec) and impacted in a box of dry sand. Measurements of three components of acceleration as well as high-speed photography were used to describe the behavior of the materials.

SYMBOLS

a	acceleration, g units
d	total distance to stop for any acceleration time history, in.
d_1	distance to accelerate to a given level, in.
d_2	distance at constant acceleration until velocity is zero, in.
f_n	natural frequency, cycles/sec
g	unit of acceleration, 386.4 in./sec^2
k	spring constant, lb/in.
l	length of specimen in crushing direction, in.
Δl	incremental change in length of specimen, in.
t	time, sec

V_o velocity at impact, in./sec

V_1 velocity at end of g rise

γ onset rate of acceleration, da/dt

Subscript:

max maximum

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INSTRUMENTATION

The basic instrumentation consisted of three accelerometers mounted on a stiff aluminum bracket to measure three components of acceleration. In addition to the accelerometers, an impact switch was installed to synchronize the acceleration records with high-speed movies. This instrumentation package shown in figure 1 was installed at the center of gravity of each drop model under study. Accelerometer outputs were fed to a carrier amplifier system and recorded on galvanometer elements installed in an oscillograph. The vertical accelerometer had a peak acceleration capability of 100 g with a system response flat to 350 cycles/sec. The other two components were measured with 20 g accelerometers having a system response flat to 200 cycles/sec.

The impact of the drop models in the sand was photographed with a movie camera operating at 1,000 frames per second. A general view of the test setup is shown in figure 2.

The normal or vertical acceleration is measured along the Z-axis. Accelerations arbitrarily called head to toe are measured along the X-axis, and the side-to-side accelerations are measured along the Y-axis.

RELATIONSHIP OF ACCELERATION TO ONSET RATE

Maximum or peak acceleration as well as onset rate (da/dt) determine man's tolerance to rapid acceleration (ref. 2). The physical relationship of these two parameters will show what compromises can be made between the two for the stopping distance available. To date there is little physiological information to allow much in the way of trading onset rate for maximum g and conversely.

The relationship of these parameters for a range of stopping distance from 4 to 8 inches is shown in figure 3 for an impact velocity of

30 ft/sec. The minimum g, infinite onset point is, of course, a rectangular time history and represents the most efficient use of stopping distance. The end point at maximum g on each curve is a triangular time history and with any practical material would be a spring with its attendant rebound problem. Points in between the two extremes represent trapezoidal time histories with specific g onset rates and some finite time of crushing at constant g. All these time histories would have infinite "offset" rates of acceleration, for which there is no physiological information. Practically, however, this would be difficult to achieve and so may be of no consequence. The equations used in arriving at this set of curves are presented in the appendix.

The curves in figure 3 immediately suggest the possibility of two distinct regions. One region of high onset rate and medium g (for protecting materials) is divided roughly from the lower onset rate and higher g (for protection of man) by a line through the point where the slope of the curves changes rapidly. Certainly, when working with a fixed stopping distance, any trading of onset rate for maximum g above this line produces little gain.

The generally accepted tolerance limit of 1,500 g/sec and the maximum of 40g is indicated in figure 3. This condition requires 8.54 inches of total travel, of which 7.78 inches is used in attaining the maximum g and 0.76 inch remains for crushing, or failure at constant acceleration. The requirement here results in more of a spring than in a crushable structure; in fact, the onset rate is equivalent to a 9 cycles/sec spring. Such a specification thus requires a considerable distance to stop, as well as the likelihood of having the spring-rebound problem to contend with.

RESULTS AND DISCUSSION

The choice of materials for load alleviation has been based on static stress-strain characteristics. The slope of the curve above the proportional limit determines how much of the material may be used. The amount of resiliency after the load is removed from a specimen indicates whether rebound may be a problem. The initial slope of the stress-strain curve determines the spring constant of the material, from which the natural frequency of the impact model can be determined. If the natural frequency is known, the rise time for the acceleration can be evaluated. This is apparent from the concept that rise time for acceleration of a spring system is approximately one-quarter of the period of the natural frequency.

Foamed Plastics

Stress-strain curves for two foamed plastics, a rigid and a semirigid type, are shown in figure 4. The difference in characteristics of the two plastics is apparent since the rigid plastic requires a reasonably high stress to reach its proportional limit and then crushes with constant stress until it becomes very stiff; and though not shown in the figure, much less of its original thickness is restored after load removal than is restored of the semirigid plastic. The semirigid plastic, of course, is not nearly so stiff and it behaves more like a spring. Removal of the load returns nearly all of the original height of the material.

The characteristics of the rigid plastic indicate that only about 60 percent of the thickness can be used before the material becomes very stiff. The slope of the curve up to the proportional limit indicates that the material would be a stiff spring. The value of the stress at the proportional limit (approximately 23 lb/sq in.) indicates that with a static loading of 1.4 lb/sq in. the material would fail at about 16g; the stress at failure equals the product of static loading and g. Using an 8-inch height of material with a spring constant k of 8,750 lb/in. for this loading would yield a natural frequency f_n of 24 cycles/sec with a rise time of 0.0103 second. The spring constant is the product of the initial slope of the stress-strain curve and the cross-sectional area of the material divided by the depth of the material sample.

The acceleration time history of a rigid plastic model, as just described, impacting in sand from a height of approximately 14 feet is presented in figure 5. The weight was a 10- by 10- by 4-inch lead block with the instrumentation bracket mounted at its center of gravity. The impact was not as flat as desired as indicated by the X- and Y-components of acceleration and the shape of the plastic after impact. The rise time to initial failure, 22g, was about 0.007 second which corresponds to a value of f_n of 36 cycles/sec compared with a calculated value of 24 cycles/sec. After first failure, the acceleration time history increased slower until bottoming occurred on one corner. The shape of the acceleration time history of this rather simple model seems to follow the stress-strain characteristics reasonably well until bottoming occurs. There was, for this case, some load alleviation from the sand. This is apparent from energy considerations, since the energy dissipation in the material is less than the kinetic energy of the drop model by about 10 percent.

The shape of the stress-strain curve for the semirigid plastic, particularly the low stress level for maximum strain utilization, offered an opportunity to design an impact model to support a loading equivalent to man.

A solid dummy was constructed of wood and leaded to weigh 62.4 lb/cu ft, representative of man. A fiber-glass form was molded to the maximum diameter of the dummy with a minimum-size lip on the form so that it would have as small an area as possible for the dummy's weight. A photograph of the model is shown in figure 6. The fiber-glass form, or couch, is one of the concepts considered in supporting a man so that there will be no relative motion of the body to the couch form during impact. The dummy assembly weighed 33 pounds, and the area of the support was 158 square inches with the very low static loading of 0.21 lb/sq in. The plastic was molded to the couch with overall dimensions of 14 inches long, 23 inches wide, and 14 inches deep with a total of 10 inches below the bottom of the dummy. Static tests of the completed model resulted in considerably different characteristics than the simple-compression sample of figure 4. The new stress-strain curve is compared with the simple-compression case in figure 7. The model shows much stiffer characteristics, and the increased initial slope of the curve indicates an increase in the onset rate of acceleration.

Drop tests from a height of 14 feet onto dry sand resulted in the acceleration time history presented in figure 8. The drop was relatively flat as indicated by the small values of the sidewise components of the acceleration. In this case, the range of the vertical accelerometer was exceeded (70g) as shown by the dotted line in figure 8. Since a new lower range accelerometer was installed because of prior instrument failure, the peak value is estimated and shown on the curve at a value above 80g. Use of the stress-strain curve indicates that with the static loading and the measured g the material was stressed up to 35 percent strain. The total rise time for the acceleration, approximately 0.009 second, is the rise time that is calculated by using the initial slope of the stress-strain curve rather than the variable slope indicated by the stress-strain curve. Considerable differences exist between samples of this material, which is foamed in place. Local airholes and hard spots in the material may contribute to this inconsistency in the data. There was considerable rebound as indicated by the acceleration. The area under the curve after initial impact indicates that there was an initial vertical rebound velocity as high as 5 ft/sec.

Foamed plastics require considerable depth to provide a given stopping distance, and for an application such as a reentry capsule this depth is not available. Rebound is most likely with these materials and requires additional protection for an occupant. If depth is available and rebound is controlled, the plastics can be made soft enough to obtain a low onset rate of acceleration.

Aluminum Honeycomb

The stress-strain curve for 3003 aluminum honeycomb with 3/8-inch cell size and 0.0007 gage material is shown in figure 9. The ratio of stress to strain up to failure is very high and indicates that it would give a very high rate of onset of acceleration. The material is usable to within 75 percent of its depth as indicated by this figure.

The strength of this material indicates that a static loading of 1 lb/sq in. would allow failure at about 27g. Accordingly, a 6.5-inch square of honeycomb 8 inches deep was loaded with a 42-pound lead weight for a dynamic test. The honeycomb was sandwiched between two pieces of wood and held together with bungee cords. The accelerometer bracket was located at the center of gravity of the lead block mounted on top of the wood as shown in figure 10.

The time history of impact of this model is shown in figure 11(a) for all three components of acceleration. The onset rate is almost infinite as shown by the vertical-acceleration trace and as indicated by the stress-strain curve. For such an impact a rectangular time history with a maximum of about 27g would be expected for the amount of material thickness available for crushing. Initial failure occurred at 24g which with a static loading of 1 lb/sq in. closely matches the proportional limit of the material. After initial failure or "accordioning" of the column, the load is relieved to about 14g before the load builds up and there is another failure. This successive increase and decrease in load is apparently a result of successive accordioning progressing through the thickness of the honeycomb. The frequency, however, is not necessarily that of the successive accordions, since the movies indicate that the accordioning is at a much higher frequency. This is more likely the natural frequency of the stiff instrument bracket. It is thought that a man subjected to this time history would feel the results shown by the faired line in the time history. There is a small amount of rebound evident in the record which amounts to less than 3 ft/sec.

An indication that this time history may be altered is seen in figure 11(b) where a model identical to the one in figure 11(a) was used. In this drop the model impacted with the bottom surface inclined at approximately 15° from the horizontal. The reduced area of initial contact started the material failure at a somewhat lower stress. In an attempt to reduce the onset rate of acceleration for a flat impact, the area at the bottom of the 6.5- by 6.5- by 8.0-inch column was reduced to 4.5 by 4.5 inches. This was accomplished by tapering the honeycomb from the original area at the midpoint in height to the new dimension at the bottom. The local stress for failure of this new area with the 42-pound weight should allow failure to begin at 12g; however, the record in figure 11(c) indicates that failure occurred at 17g. The overall record indicates a considerable reduction in rate of onset of acceleration compared with that of the unaltered model. Although the drop was reasonably flat, there were considerable side components of acceleration. In fact, the material bottomed on one side as shown by the peak in the Y-acceleration.

Another means of reducing the onset rate of acceleration involves the use of the semirigid plastic in sandwich with the honeycomb. A record of such a drop is shown in figure 12. This model consisted of 4 inches of aluminum honeycomb and 4 inches of foamed plastic with a metal plate separating the two materials. The static loading was 1.0 lb/sq in. The materials were again sandwiched between two pieces of wood with a lead weight and the accelerometer bracket mounted on the top board. The onset rate of this combination followed the simple one-degree-of-freedom spring constant for springs in series. One of the problems inherent in any work of this nature is indicated by the high peak in the records indicating that the dummy bottomed before the impact velocity had been dissipated. The instability of a column failure is likely to cause premature bottoming, unless some special effort is made to prevent it. The use of multiple columns, spaced somewhat by trial, would likely solve this problem.

CONCLUDING REMARKS

A limited investigation has been made to determine the characteristics of three materials to see how they can be applied for human protection at low impact speed. As a result, if given man's physiological tolerance to abrupt acceleration, which has not yet been well defined, an alleviation system can be designed.

Foamed plastics require considerable depth to provide a given stopping distance for impact alleviation; in addition, some control of the rebound would be required for human protection. Plastics can be made soft enough to obtain the low onset rates of acceleration that may be necessary for man where depth is not limited.

Aluminum honeycomb is an efficient material for impact load alleviation, since up to 80 percent of the depth is usable, and there is very little rebound. The stiffness of this material results in a very high initial onset rate of acceleration which may be controlled by reducing the initial area of contact to provide earlier failure.

Static characteristics can be used within engineering accuracy to predict the dynamic behavior of crushable materials. The use of high-speed movies best shows the way these materials react. All the tests were meant to result in a flat impact. When this was not the case, other problems such as premature local bottoming of the load occurred. In the general usage of any of these materials for human protection an allowance must be made to take care of bottoming.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., August 10, 1959.

APPENDIX

ACCELERATION TIME HISTORIES

Rectangular-Acceleration Time History

A rectangular-acceleration time history assumes infinite onset rate of acceleration with the velocity used up at constant acceleration. For this case, the equation for constant acceleration is applicable where

$$V_o^2 = 2a\,d$$

$$a = \frac{V_o^2}{2d}$$

$$d = \frac{V_o^2}{2a}$$

Trapezoidal-Acceleration Time History

The general case where trapezoidal acceleration is applied at rates less than infinite, with corresponding variation in amount of constant acceleration, results in the equations

$$d_1 = V_o t - \frac{1}{2} \int \gamma t^2 dt$$

$$d_1 = V_o t - \frac{\gamma t^3}{6} = V_o t - \frac{a t^2}{6}$$

Finding the total distance to stop d requires that the velocity at the end of g rise be found. Thus,

$$dV_o = V_o - V_1 = \gamma t\ dt$$

$$V_o - V_1 = \gamma \int t\ dt = \frac{\gamma t^2}{2}$$

Since the onset rate of acceleration γ is assumed and time t is known, the new velocity V_1 can be found thus, from constant-acceleration relations,

$$d_2 = \frac{V_1^2}{2a}$$

$$d = d_1 + d_2$$

For purposes of producing figure 3, peak accelerations were assumed and the onset rate of acceleration was varied. The resulting distances were plotted against acceleration in g units for constant onset rate of acceleration in g/sec. These data were simply cross-plotted at constant stopping distance to give figure 3.

REFERENCES

1. Roffee, Barton H.: Aerial Delivery System for Combat Rations With Paper Honeycomb as an Energy Absorbing Material. Project No. 7-87-03-004B, Quartermaster Food and Container Inst. for the Armed Forces, Feb. 9, 1956.

2. Hess, John L.: The Approximation of the Response of the Human Torso to Large Rapidly Applied Upward Accelerations by That of an Elastic Rod and Comparison With Ejection Seat Data. Rep. No. ES 26472, Douglas Aircraft Co., Inc., Nov. 26, 1956.

3. Eiband, A. Martin: Human Tolerance to Rapidly Applied Accelerations: A Summary of the Literature. NASA MEMO 5-19-59E, 1959.

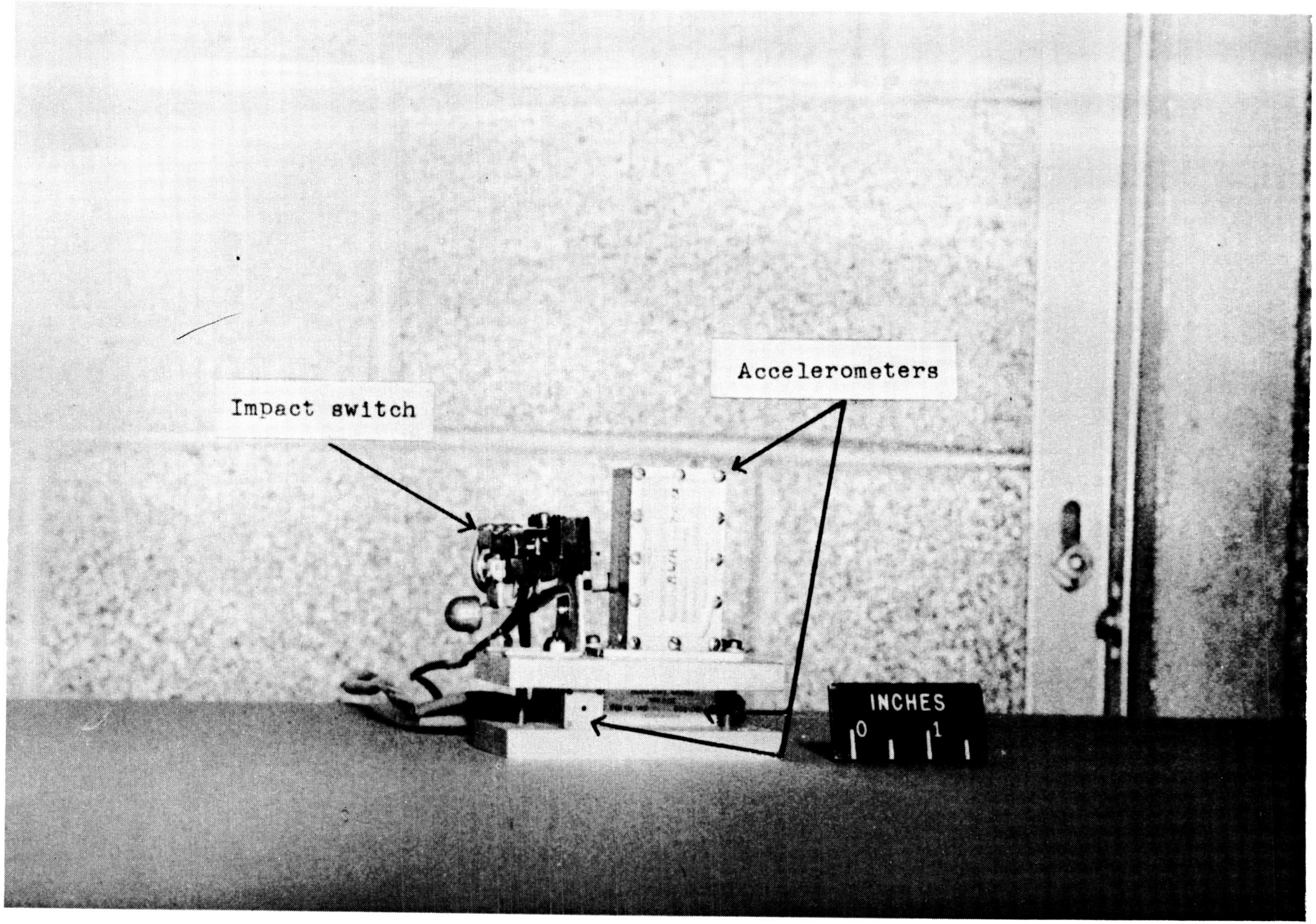

Figure 1.- Instrumentation package showing accelerometers and impact switch. L-59-3452.1

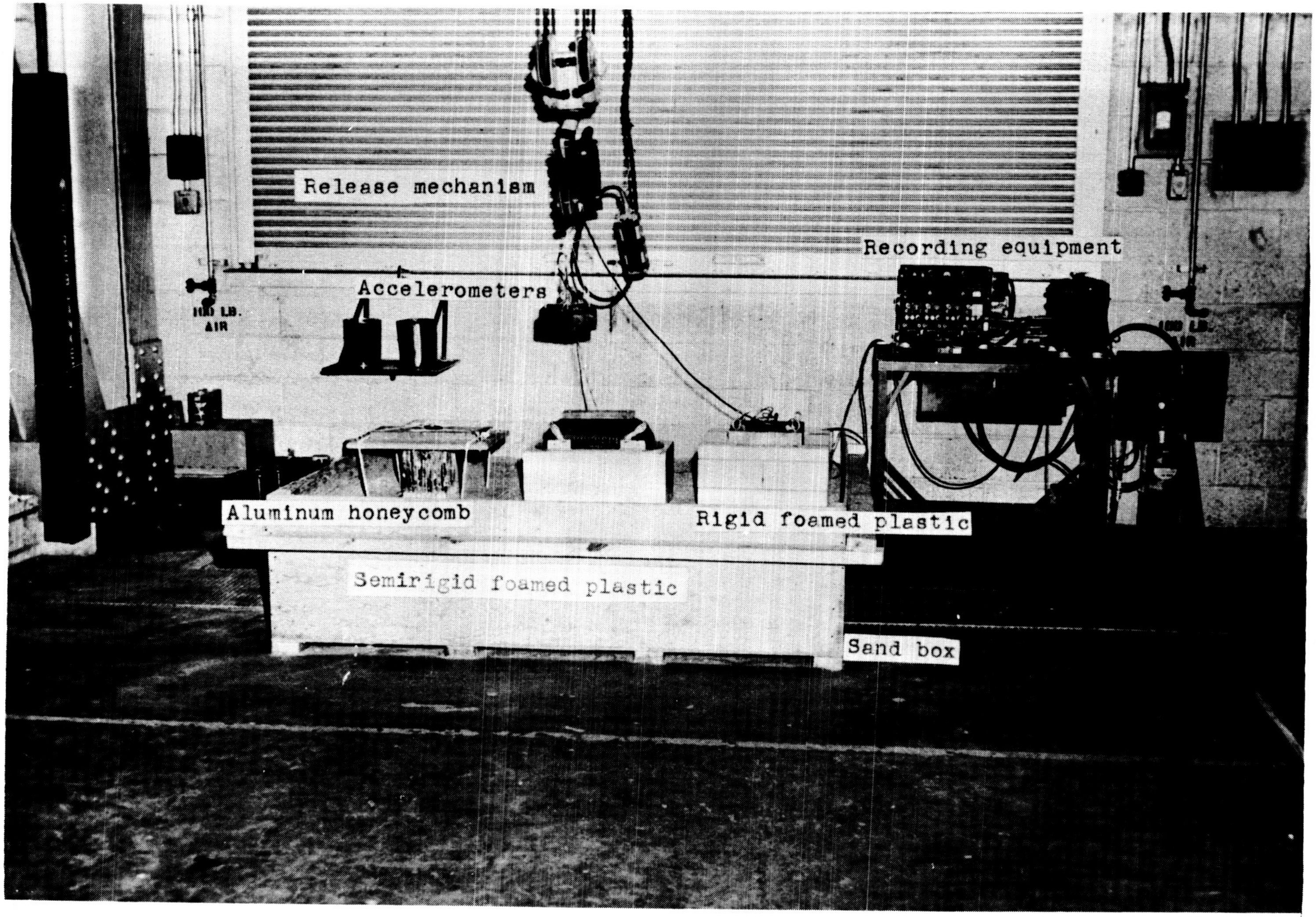

Figure 2.- General view of test area. L-59-3451.1

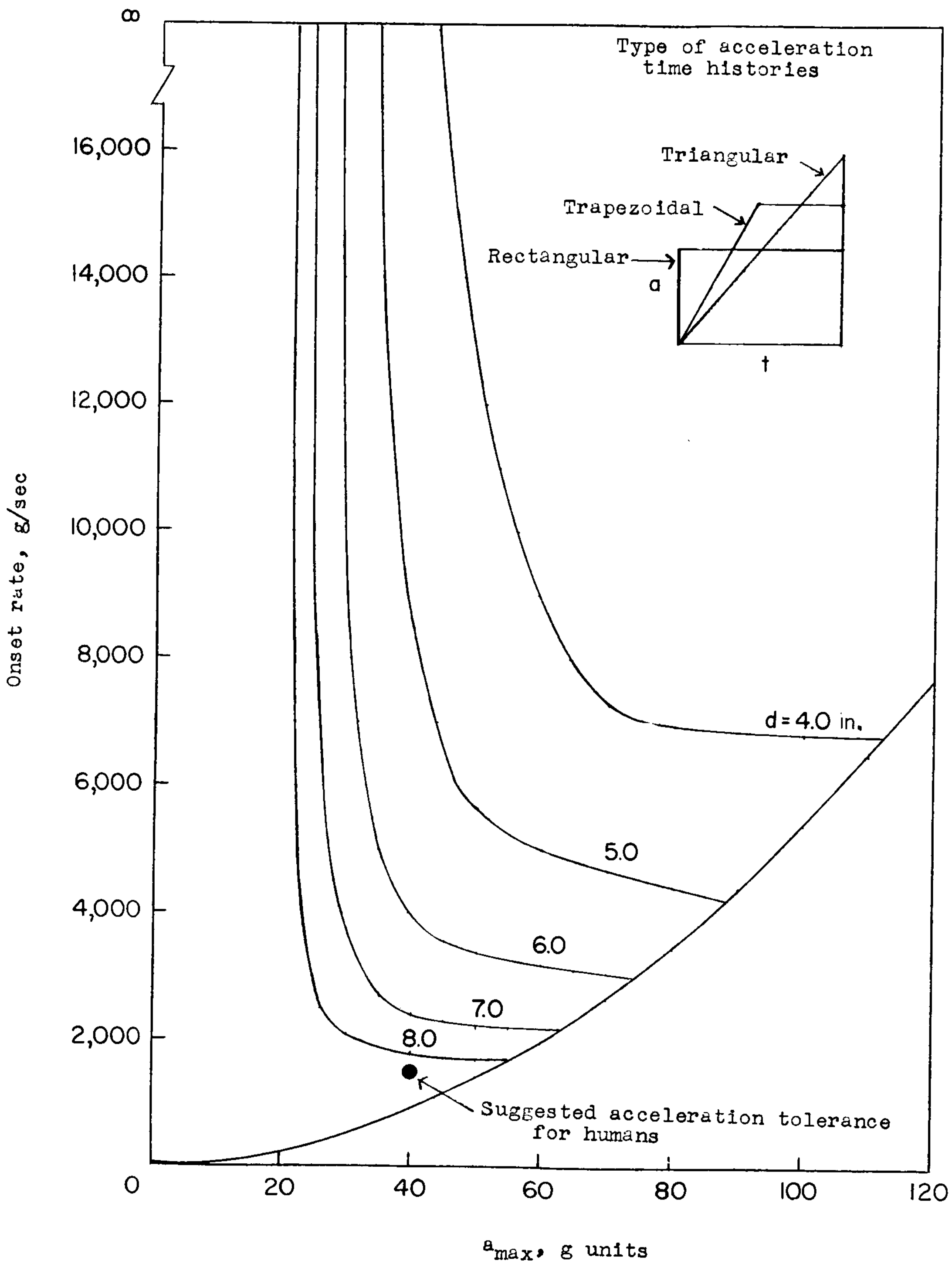

Figure 3.- Variation of maximum acceleration and onset rate for constant values of stopping distance for an impact velocity of 30 ft/sec.

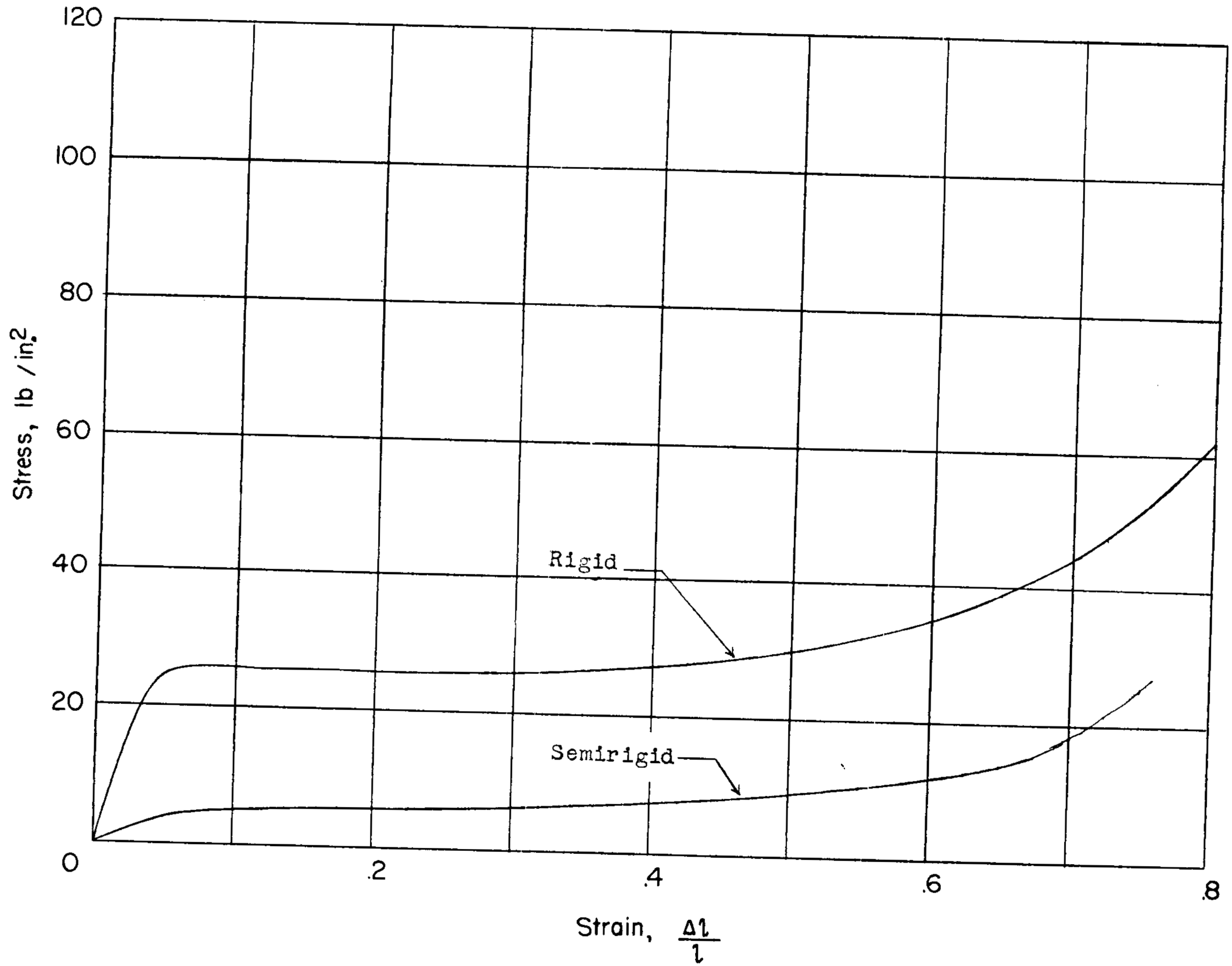

Figure 4.- Stress-strain curve for two foamed plastics.

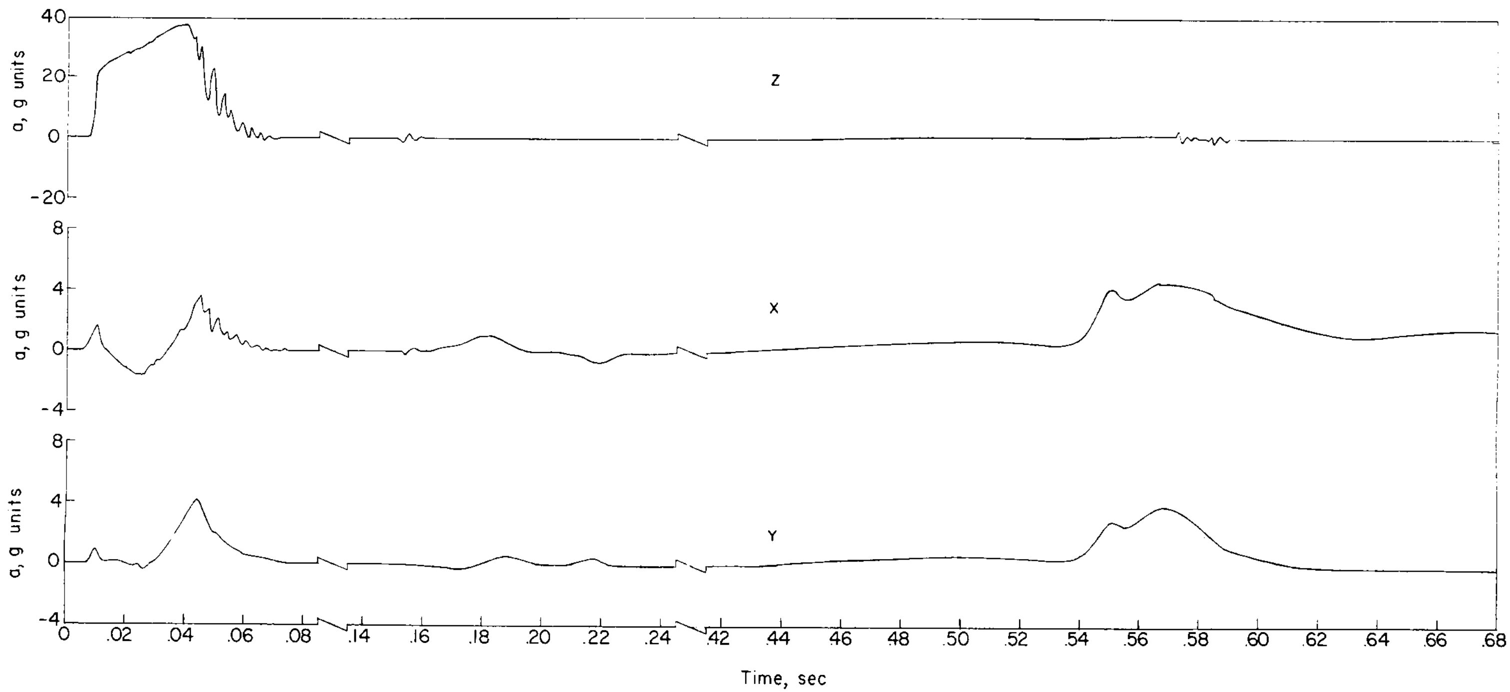

Figure 5.- Acceleration time history of rigid plastic model impacting in sand from a height of approximately 14 feet.

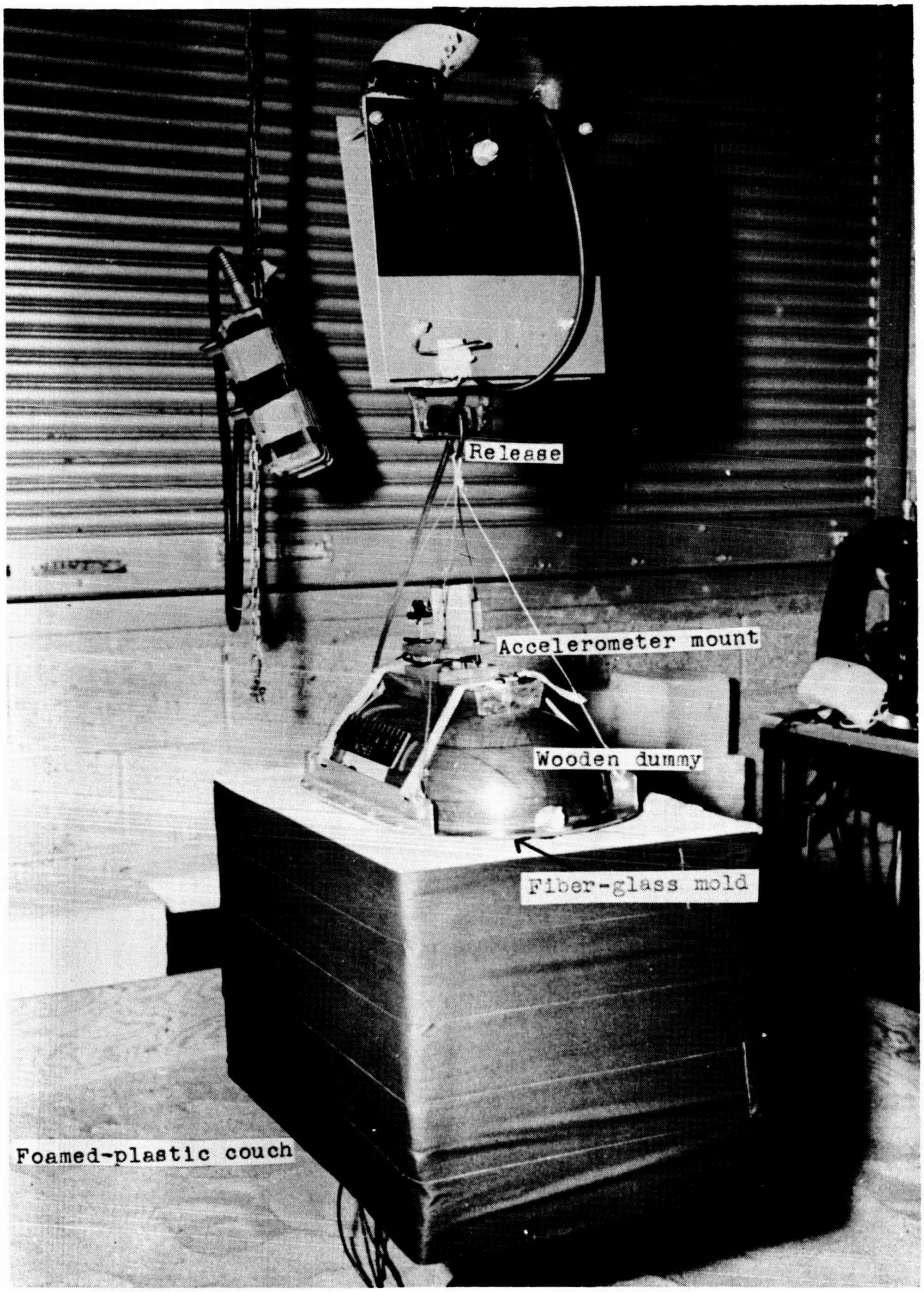

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Figure 6.- Photograph of semirigid plastic model with dummy representing man's weight distribution.

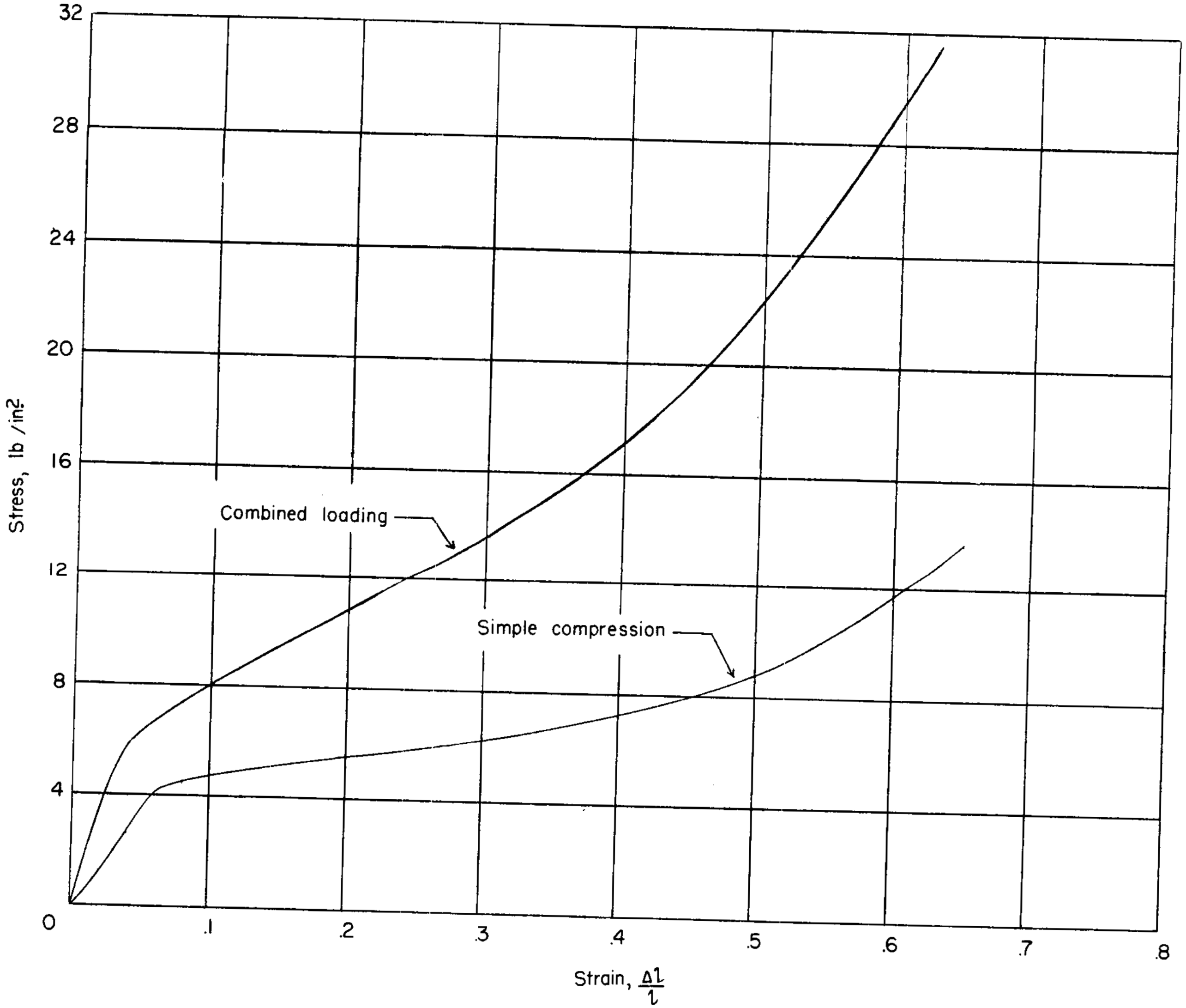

Figure 7.- Stress-strain curve for different loading conditions of semirigid foamed plastic.

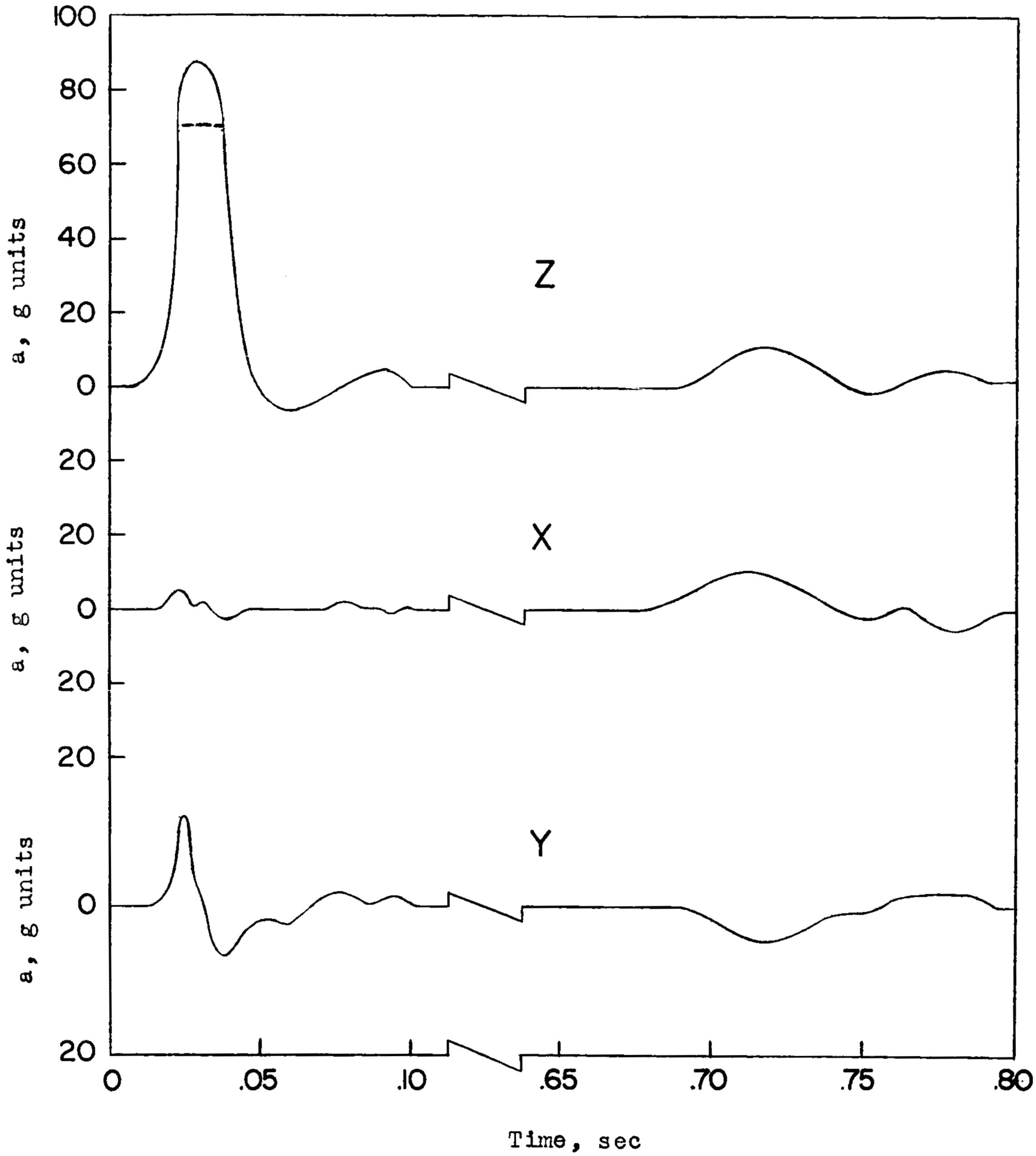

Figure 8.- Acceleration time history of semirigid foamed-plastic drop model. Dotted line indicates that range of accelerometer was exceeded.

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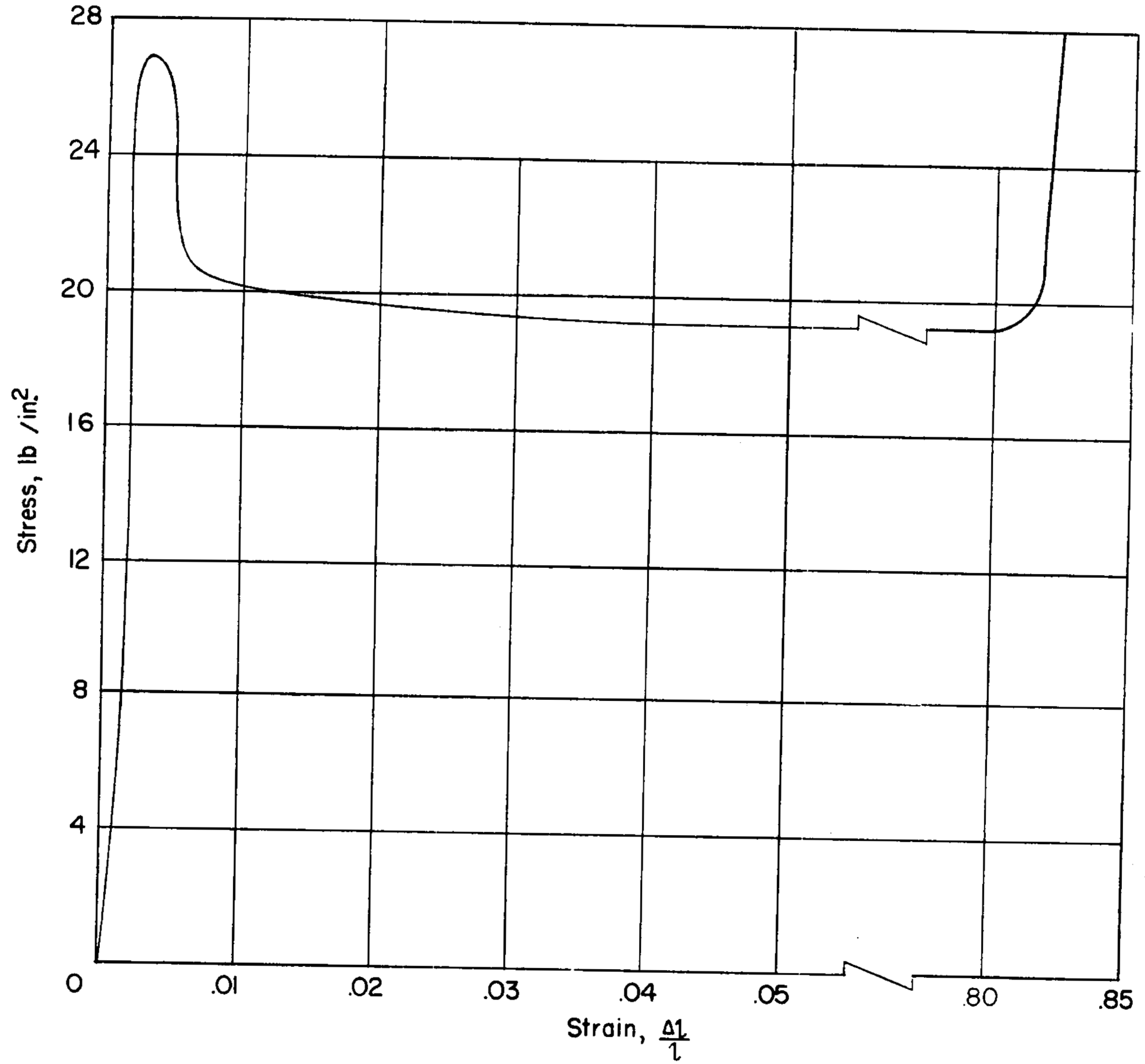


Figure 9.- Stress-strain curve for aluminum honeycomb. 3/8-inch cell size; 0.0007 gage foil.

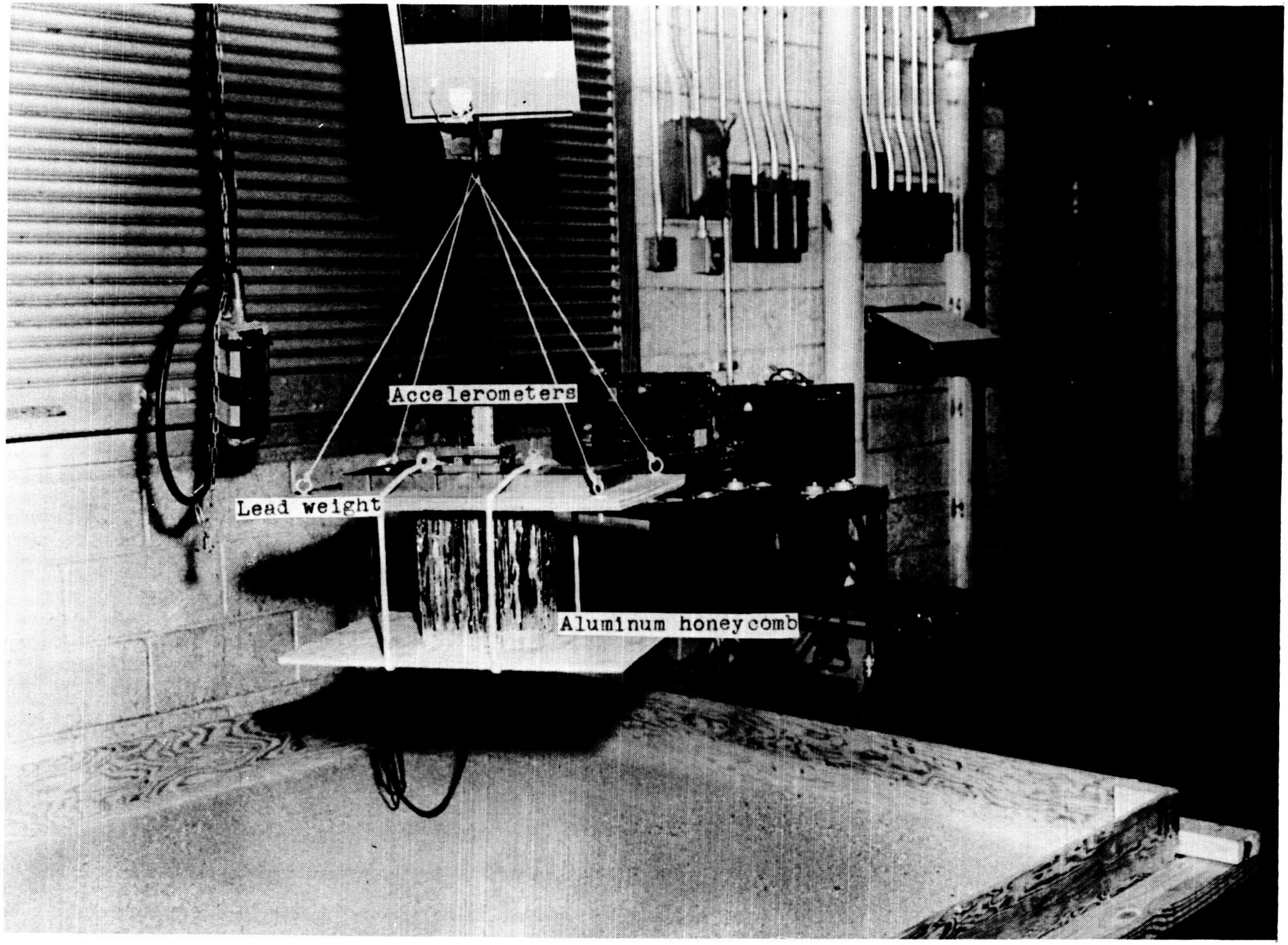
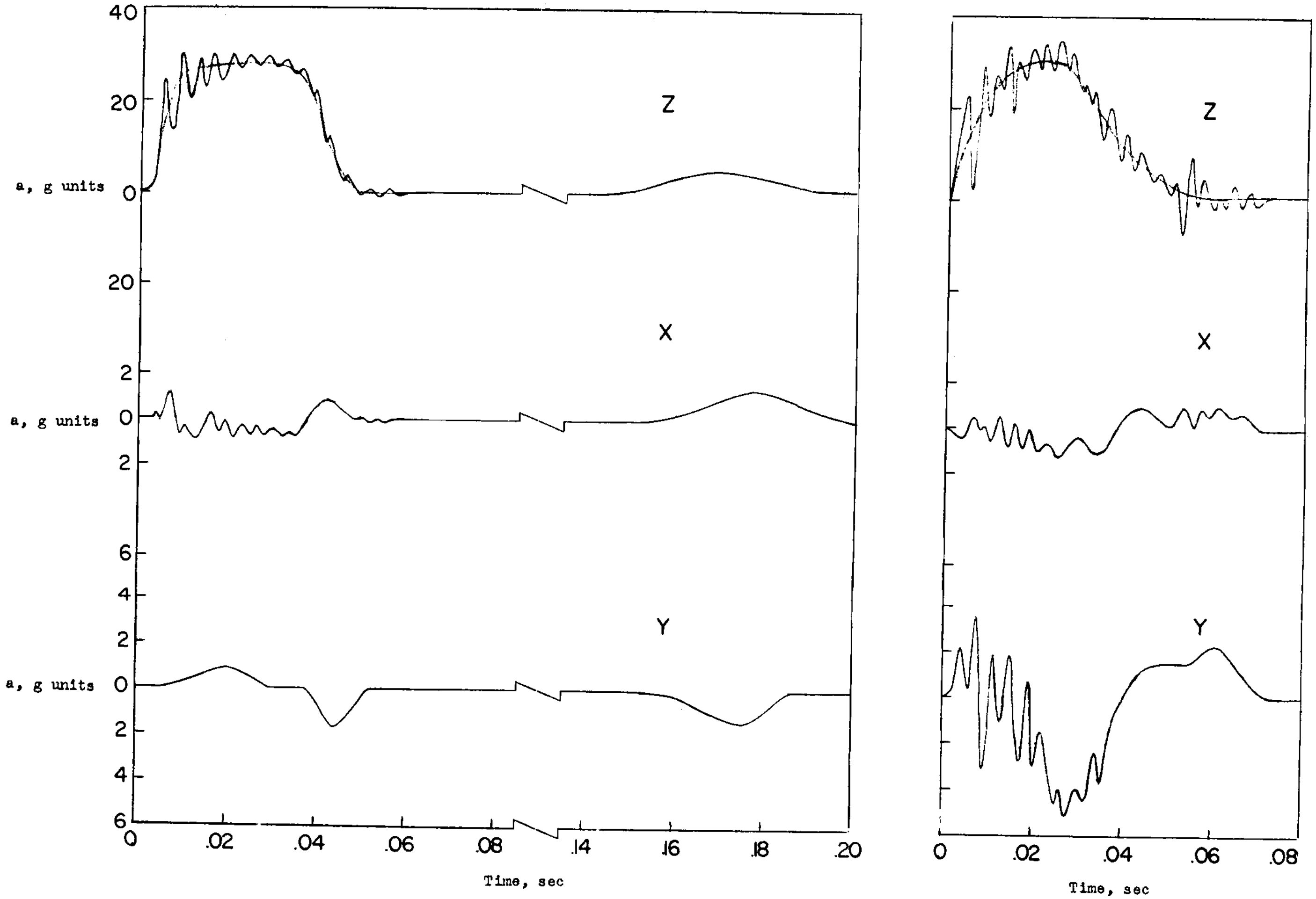


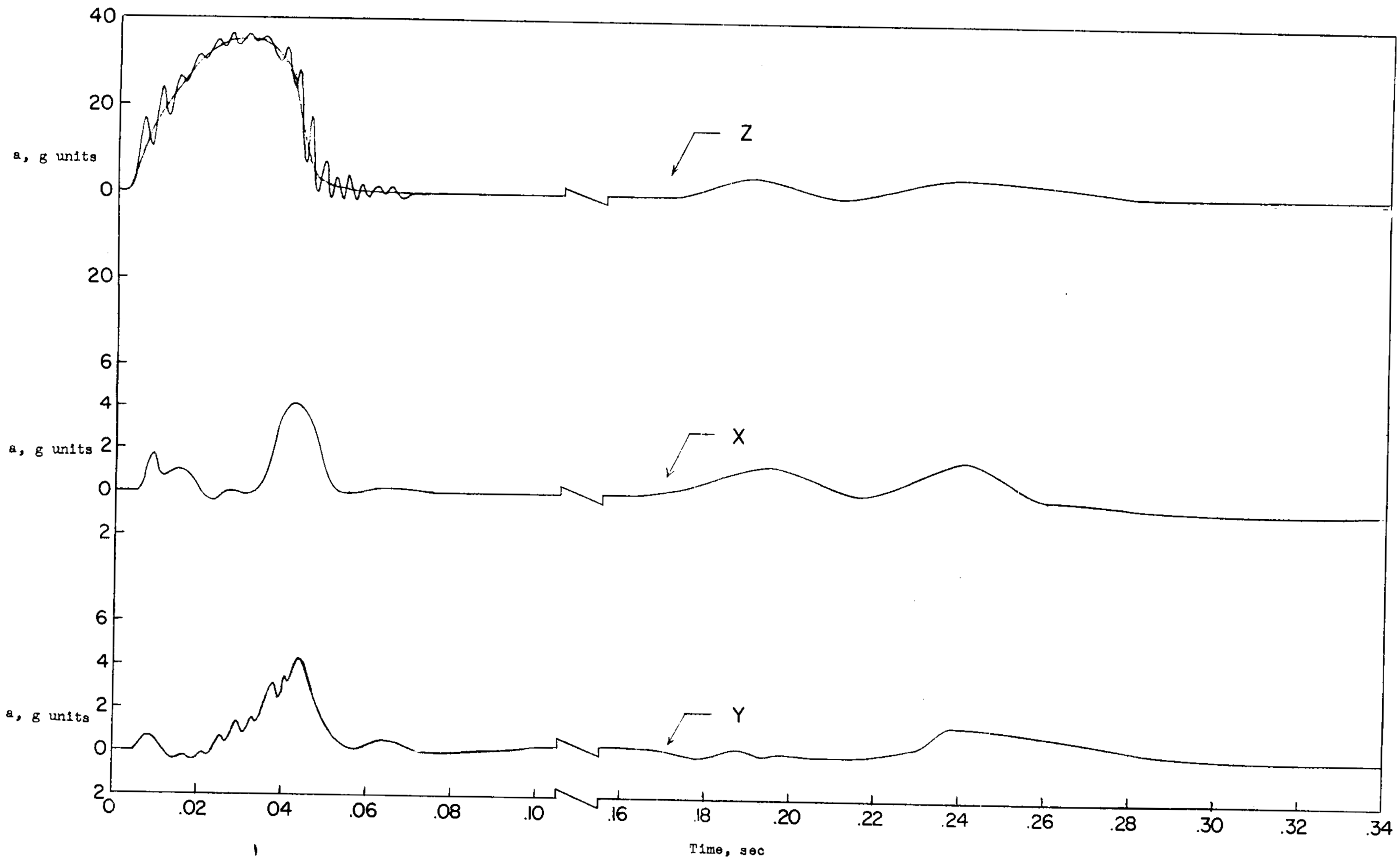
Figure 10.- Dynamic test rig for aluminum honeycomb. L-59-3449.1



(a) Model having dimensions of 6.5 inches long, 6.5 inches wide, and 8.0 inches deep when impacting almost horizontally.

(b) Model impacting at an angle to horizontal.

Figure 11.- Acceleration time history of honeycomb drop model.



(c) Model with reduced area of contact.

Figure 11.- Concluded.

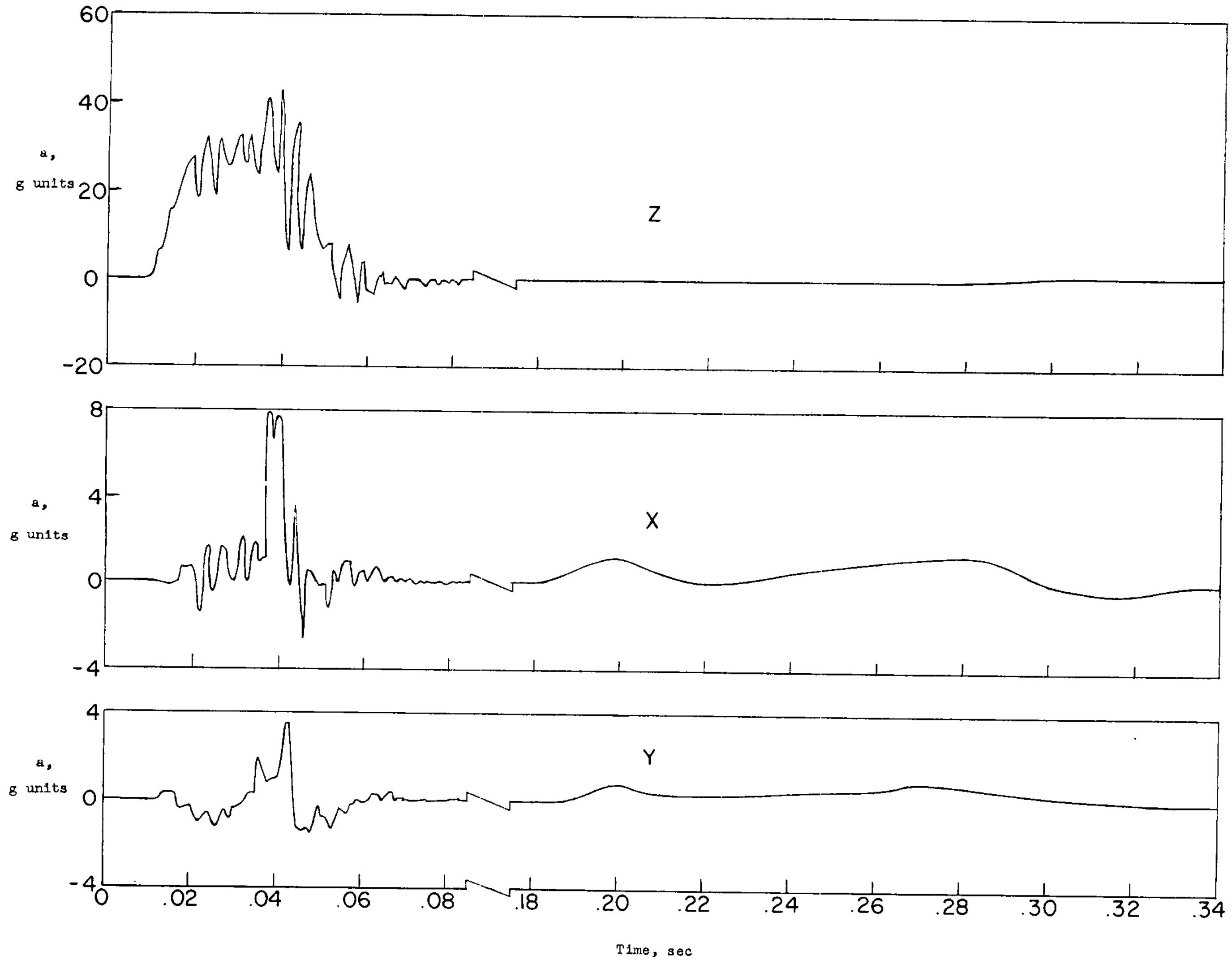


Figure 12.- Acceleration time history of combined honeycomb and semirigid plastic drop model.